Individual limb work does not explain the greater metabolic cost of walking in elderly adults

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Ortega JD, Farley CT. Individual limb work does not explain the greater metabolic cost of walking in elderly adults. J Appl Physiol 102: 2266–2273, 2007. First published March 15, 2007; doi:10.1152/japplphysiol.00583.2006.—Elderly adults consume more metabolic energy during walking than young adults. Our study tested the hypothesis that elderly adults consume more metabolic energy during walking than young adults because they perform more individual limb work on the center of mass. Thus we compared how much individual limb work young and elderly adults performed on the center of mass during walking. We measured metabolic rate and ground reaction force while 10 elderly and 10 young subjects walked at 5 speeds between 0.7 and 1.8 m/s. Compared with young subjects, elderly subjects consumed an average of 20% more metabolic energy (P = 0.010), whereas they performed an average of 10% less individual limb work during walking over the range of speeds (P = 0.028). During the single-support phase, elderly and young subjects both conserved ~80% of the center of mass mechanical energy by inverted pendulum energy exchange and performed a similar amount of individual limb work (P = 0.473). However, during double support, elderly subjects performed an average of 17% less individual limb work than young subjects (P = 0.007) because their forward speed fluctuated less (P = 0.006). We conclude that the greater metabolic cost of walking in elderly adults cannot be explained by a difference in individual limb work. Future studies should examine whether a greater metabolic cost of stabilization, reduced muscle efficiency, greater antagonist cocontraction, and/or a greater cost of generating muscle force cause the elevated metabolic cost of walking in elderly adults.

biomechanics; locomotion; mechanical work; gait

ELDERLY ADULTS CONSUME MORE metabolic energy during walking than young adults (28, 35, 44, 54), but the reason is unknown. Specifically, to walk a given distance, elderly adults consume ~20% more energy per kilogram of body mass (“net mass-specific cost of transport”) than young adults (35, 36, 53) regardless of whether they have sedentary or active lifestyles (35). Although elderly adults consume more energy than young adults at all speeds, both elderly and young adults consume the least metabolic energy to walk a given distance at intermediate speeds, and they consume more energy when they use faster or slower speeds (9, 35, 36, 54). This observation suggests that similar biomechanical factors influence the metabolic cost of walking regardless of age. This study investigates whether an age-related difference in walking mechanics causes elderly adults to consume more metabolic energy than young adults.

During walking, stance limb muscles perform mechanical work to lift and accelerate the body’s center of mass, and this work is closely related to the metabolic cost (17, 18). During the single-support phase of walking, the stance limb performs relatively little mechanical work due to inverted pendulum-like energy exchange as the center of mass vaults over a nearly rigid strut-like stance limb. In contrast, during the double-support phase, the limbs perform substantial work to redirect the center of mass from one inverted pendulum arc to the next. Specifically, the leading limb performs negative work to change the center of mass direction while the trailing limb simultaneously performs positive work to prevent the leading limb from decelerating the body (19). Because traditional measures of external work (11) do not account for the opposing work during the double-support phase, they omit ~33% of the total mechanical work performed by the stance limbs on the center of mass (i.e., “individual limb work”; Ref. 18). Given the important role of mechanical work in determining metabolic cost (11, 18), the elevated cost of walking in elderly adults may be caused by a change in walking mechanics that requires more individual limb work.

Although elderly adults perform a similar amount of external work as young adults (26, 37, 50), some kinematic evidence suggests that individual limb work may differ between elderly adults and young adults. First, the observation by previous studies that elderly adults spend more time in double support during walking than young adults (14, 29, 41, 48) suggests that the two stance limbs of elderly adults may generate opposing forces over a greater distance and therefore perform more opposing work during double support than young adults. Second, some studies have shown that elderly adults take wider steps than young adults (12, 22, 41), although other studies have found little or no difference (20, 21, 24, 56). Taking wider steps requires more individual limb work to redirect the center of mass in the mediolateral direction during double support (17, 27). Even small increases in step width may have important effects because individual limb work and metabolic cost increase with the square of step width (17, 27). Therefore, a given percent increase in step width will cause a larger percent increase in individual limb work. Finally, some studies show that elderly adults take 2–4% shorter steps at a given walking speed than young adults (15, 16, 28), but other studies show no difference (29, 35, 48). Although it is not known whether changing step length at a given speed affects individual limb work, experimental data from young adults show that taking shorter steps slightly affects external work (7, 39). However, for the observed 2–4% decrease in step length in elderly adults (15, 16, 28), previous studies suggest that the effect on external work and metabolic cost would be very small (7, 39).

Our study tested the hypothesis that elderly adults consume more metabolic energy during walking at all speeds than young adults because they perform more individual limb work on the
center of mass at all speeds. To test our hypothesis, we determined metabolic cost and individual limb work performed on the center of mass for healthy young adults and elderly adults walking at a range of speeds. We focused on individual limb work performed on the center of mass because it accounts for the opposing work performed during double support (19). To the best of our knowledge, this study is the first to examine individual limb work during walking in elderly adults.

MATERIALS AND METHODS

Experimental design. We collected metabolic and kinetic data for 10 healthy elderly adults [age of 76 yr (SD 4), mass of 63.2 kg (SD 8.9), height of 1.68 m (SD 0.08), body mass index of 22.6 (SD 2.1)] and 10 healthy young adults [age of 25 yr (SD 4), mass of 68.9 kg (SD 9.5), height of 1.75 m (SD 0.08), body mass index of 23.8 (SD 2.4)] walking at 5 different speeds. Subjects were screened based on a standard lifestyle and medical questionnaire and examined by a physician to determine their eligibility (1). Subjects were excluded if they were classified by the physician as having a history of falls or smoking, a body mass index $>28$, high blood pressure ($>140/90$ mmHg), orthopedic or neurological conditions, or a heart condition, or if they were taking medication that causes dizziness. In addition, elderly subjects performed a physician-supervised graded exercise test to rule out the presence of overt cardiovascular disease. Before participation, all subjects gave their written informed consent. The University of Colorado Committee for the Protection of Human Subjects approved this protocol.

Each subject participated in two testing sessions. In the first testing session, subjects performed one standing trial, walked on a motorized treadmill for at least 10 min to become familiar with treadmill walking (52), and finally walked on the treadmill at five randomly ordered speeds (0.7, 1.0, 1.3, 1.5, and 1.8 m/s) while we measured oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and step frequency. During the second testing session, we measured ground reaction force as subjects walked on a walkway at each of the five randomly ordered prescribed speeds, and we used these data to determine individual limb work. Two of the elderly subjects could not complete the 1.8 m/s trials. For each successful trial, we calculated the net change in forward velocity using the horizontal ground reaction force impulse for each step. On average, we found that the net change in forward velocity for the steps included in the study was $-0.03$ m/s (SE 0.001).

We determined step width from the instantaneous center of pressure under each foot. We defined step width as the lateral distance between the center of pressure under the left foot and right foot at approximately midstance of sequential footfalls. We approximated midstance as the time when the horizontal (fore-aft) ground reaction force crossed zero during single support. Because individual limb work depends on the lateral distance between the force vectors under the two feet (17), this measure of step width is most appropriate for this study.

We determined individual limb power output from the dot product of the individual limb ground reaction force and the center of mass velocity (2, 19). Before analysis, a fourth-order zero-lag low-pass Butterworth filter with a cutoff frequency of 100 Hz was used to filter the ground reaction force signals. To calculate the instantaneous center of mass velocity in each direction (vertical, horizontal, lateral), we first determined each component of the “combined limb ground reaction force” by summing the individual limb ground reaction force for both limbs over a step. We used the combined limb ground reaction force components to determine the center of mass acceleration in each direction. Subsequently, we integrated each component of the acceleration with respect to time to determine the instantaneous center of mass velocity (6, 10).

We calculated the positive individual limb work performed on the center of mass from the power output of each limb. The positive work performed by each limb on the center of mass was calculated by integrating each limb’s power with respect to time for the time intervals when its power was positive (19). We used this technique to determine positive individual limb work for the whole step ($W_{\text{limb,step}}$, double support ($W_{\text{limb,ds}}$, and single support ($W_{\text{limb,ss}}$) by restricting the integration to the time interval of interest. We calculated the positive limb work because the positive limb work reflects the net positive external work performed on the center of mass to maintain walking speed as well as the positive mechanical work performed by the trailing limb to compensate for the simultaneous negative work performed by the leading limb during the double-support phase. For this study, we did not include negative individual limb work because the total positive limb work must be equal to the total negative limb work to maintain walking speed, and thus it would be a redundant calculation.

We calculated the mechanical energy fluctuations of the center of mass from its velocity and displacement (9, 11, 37, 43). First, we calculated the acceleration in each direction from each component of the combined limbs ground reaction force. As described above, we determined the instantaneous velocity in each direction by integrating acceleration component with respect to time. We determined the instantaneous vertical displacement by integrating the vertical velocity with respect to time (6, 10). Subsequently, we calculated the gravitational potential energy from the product of body mass, gravitational acceleration, and the change in center of mass height relative to heel strike. Next, we calculated kinetic energy from body mass and the resultant center of mass velocity. By taking the sum of gravi-
tional potential energy and kinetic energy at each instant over the step, we calculated the total energy of the center of mass ($E_{tot}$). Finally, we determined the sum of the positive fluctuations in total energy over the whole step ($\Delta E_{tot,step}$), double support ($\Delta E_{tot,ds}$), and single support ($\Delta E_{tot,ss}$) (6, 11).

We determined the positive work performed during double support to transition from one inverted pendulum arc to the next ("transition work") from the positive individual limb work and the total energy of the center of mass. Transition work corresponds to the positive work performed by the trailing limb that is mathematically cancelled by the simultaneous opposing work by the leading limb (19). Consequently, we calculated transition work from the difference between the total positive individual limb work and the sum of the positive fluctuations of the center of mass total energy during double support. In contrast to double support, all individual limb work performed during single support changes the center of mass mechanical energy because only one foot is on the ground. All mechanical work values are expressed per kilogram body mass and per meter traveled (J·kg$^{-1}$·m$^{-1}$).

**Inverted pendulum mechanics.** We evaluated inverted pendulum mechanics for only the single-support phase because the center of mass passes over a rigid strut-like stance limb like an inverted pendulum during this phase. In contrast, during double support, the body does not behave like a simple inverted pendulum as it transitions from one inverted pendulum arc to the next. To evaluate the potential for inverted pendulum energy exchange during single support, we examined the relative magnitudes and timing of the mechanical energy fluctuations of the center of mass. Because there was a net change in the total energy of the center of mass over single support (see Fig. 5) unlike for a complete step or stride, it did not make sense to calculate mechanical energy "recovery" for the single-support phase to evaluate inverted pendulum energy exchange (11). Moreover, using recovery to quantify inverted pendulum energy exchange for the entire step cycle does not make sense because it ignores the opposing work performed during double support.

To assess the potential for energy exchange during single support, we compared the magnitudes of the fluctuations in gravitational potential energy and kinetic energy of the center of mass. Gravitational potential energy and kinetic energy each fluctuated once during single support (see Fig. 5), and $\Delta GPE_{ss}$ and $\Delta KE_{ss}$ corresponded to the sum of the positive fluctuations in these energies during single support. The sum of $\Delta GPE_{ss}$ and $\Delta KE_{ss}$ represented the individual limb work that would be required to lift and accelerate the center of mass during single support if no mechanical energy were exchanged via the inverted pendulum mechanism. We evaluated the reduction in individual limb work due to inverted pendulum energy exchange during single support by taking the ratio of individual limb work ($W_{limb,ss}$) to the sum of $\Delta GPE_{ss}$ and $\Delta KE_{ss}$. A value of one indicates no energy exchange, whereas a smaller ratio indicates a greater reduction in individual limb work due to energy exchange. This method gives an estimate of the potential for energy exchange but does not directly address how much work is performed by individual muscles, and one modeling study suggests that the muscle work may be substantial during single support despite the potential for energy exchange (42).

As an additional measure of the potential for mechanical energy exchange during single support, we quantified the relative timing of gravitational potential energy and kinetic energy fluctuations during single support by calculating phase angle (8):

$$\text{Phase angle} = (\Delta t) \times 360^\circ + 180^\circ \quad (1)$$

where $\Delta t$ represents the time interval between minimum kinetic energy and maximum gravitational potential energy, and $T$ represents the time interval between consecutive heel strikes. Thus when the minimum kinetic energy and maximum gravitational potential occurred simultaneously as required for optimal energy exchange, phase angle was $180^\circ$.

**Statistical analyses.** At each speed, we calculated the mean value of each mechanical variable for three steps per subject. We used repeated-measures ANOVA ($P < 0.05$) to determine statistical differences due to age and speed as well as the age-speed interaction. Bonferroni $t$-tests were used to determine differences between young and elderly subjects at particular speeds. All statistical analyses were performed using SPSS 13.0 (SPSS) software.

**RESULTS**

Elderly subjects consumed an average of 20% more metabolic energy to travel a meter than young subjects ($P = 0.010$) over the range of speeds (Fig. 1). At the speed where the net metabolic cost of transport was minimized for both groups (1.0 m/s), elderly subjects consumed 17% more metabolic energy to travel a meter than young subjects [elderly 2.18 J·kg$^{-1}$·m$^{-1}$ (SD 0.44), young 1.86 J·kg$^{-1}$·m$^{-1}$ (SD 0.19); $P = 0.011$]. The difference in net metabolic cost of transport increased with speed. Consequently, elderly subjects consumed 14 and 34% more metabolic energy at the slowest and fastest speeds, respectively, than young subjects.

Compared with young subjects, elderly subjects had similar step widths at all speeds but took shorter and more frequent steps at slow and moderate speeds (Fig. 2, A and B). Elderly subjects increased step frequency compared with young subjects [elderly 1.94 Hz (SD 0.16), young 1.82 Hz (SD 0.06); $P = 0.034$] by spending almost 10% less time in the single-limb-support phase than young subjects at average speeds across the speed range ($P = 0.010$; Fig. 2C). At all speeds, elderly and young subjects each spent a similar amount of time in the double-support phase [0.17 s (SD 0.03); $P = 0.807$; Fig. 2D] and used similar step widths [elderly 15 cm (SD 3), young 12 cm (SD 3); $P = 0.139$; Fig. 2B].

In contrast to their greater consumption of metabolic energy during walking, elderly subjects performed an average of 10% less individual limb work on the center of mass than young subjects across the range of speeds ($P = 0.028$; Fig. 3). Individual limb work increased with speed less steeply in elderly subjects than in young subjects ($P = 0.041$; Fig. 3). Consequently, both groups performed a similar amount of individual limb work at the slowest speed [elderly 0.29
J·kg⁻¹·m⁻¹ (SD 0.06), young 0.28 J·kg⁻¹·m⁻¹ (SD 0.03)], but elderly subjects performed ~13% less individual limb work than young subjects at the fastest speed [0.48 J·kg⁻¹·m⁻¹ (SD 0.13) vs. 0.55 J·kg⁻¹·m⁻¹ (SD 0.06); \(P = 0.018\)].

During the single-limb-support phase of walking at each speed, both elderly and young subjects conserved substantial mechanical energy via inverted pendulum energy exchange and performed a similar amount of individual limb work (\(P = 0.473\)) (Fig. 4A). Without inverted pendulum energy exchange, the stance limb would have to perform all of the work to lift (\(\Delta GPE_{cm}\)) and accelerate (\(\Delta KE_{cm}\)) the center of mass during the single-support phase (Fig. 4B). These positive fluctuations in gravitational potential energy and kinetic energy during the single-support phase increased with speed and were similar for both groups (Fig. 4B). However, because of substantial inverted pendulum energy exchange, the stance limbs of young and elderly subjects performed an average of only 18% (SD 4) and 22% (SD 6), respectively, of the work required to lift and accelerate the center of mass during the single support phase across the range of speeds (\(P = 0.09\) for young vs. elderly; Fig. 4C). One reason why inverted pendulum exchange was effective was that the gravitational potential energy and kinetic energy fluctuations were mostly out of phase with each other [200° (SD 3)] during single support in both groups across the range of speeds (Figs. 4D and 5). Thus much of the increase in gravitational potential energy could have occurred passively because of inverted pendulum energy exchange. Similarly, during the second half of single support, the decrease in gravitational potential energy was similar in magnitude to the simultaneous increase in kinetic energy (Fig. 5).

During the double-limb-support phase of walking when the body transitions from one inverted pendulum arc to the next, elderly subjects performed an average of 17% less individual limb work than young subjects across the speed range (\(P = 0.007\); Fig. 6A). During double support, elderly subjects performed 0.25 J·kg⁻¹·m⁻¹ (SD 0.06) and young subjects performed 0.30 J·kg⁻¹·m⁻¹ (SD 0.03) of individual limb work on average across the speed range. Double support individual limb work increased with speed less steeply in elderly subjects than in young subjects (\(P = 0.041\)). Consequently, both groups performed a similar amount of individual limb work during

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**Fig. 2.** Step frequency (A), step width (B), single-support time (C), and double-support time vs. speed (D) in young subjects (●) and elderly subjects (○). Values are means (SD). Elderly subjects took faster and shorter steps by spending less time in the single-support phase of walking. Lines are least squares regressions. *Significant differences between young and elderly subjects at a given speed, \(P < 0.05\).

**Fig. 3.** Total individual limb work (\(W_{\text{limb,step}}\)) vs. speed in young subjects (●) and elderly subjects (○). Values are means (SD). Elderly subjects performed less individual limb work than young subjects at moderate and fast speeds. Lines are least squares regressions. *Significant differences between young and elderly subjects at a given speed, \(P < 0.05\).
double support at the slowest speed, but elderly subjects performed 24% less individual limb work than young subjects at the fastest speed [elderly 0.26 J·kg⁻¹·m⁻¹ (SD 0.06), young 0.34 J·kg⁻¹·m⁻¹ (SD 0.03); P = 0.013]. Because elderly subjects performed less individual limb work during double support, they had smaller positive fluctuations in total energy (P = 0.003, Fig. 6B) and kinetic energy of the center of mass (P = 0.006, Fig. 6C) during double support than young subjects at moderate and high speeds (1.3–1.8 m/s).

During double support, individual limb work exceeded the positive fluctuation in total energy of the center of mass by a similar amount in young and elderly subjects, and this observation indicates that both groups performed similar step-to-step transition work (P = 0.887; Fig. 6D). Transition work represented the portion of positive individual limb work during double support that prevented the deceleration of the center of mass during the transition from one inverted pendulum arc to the next. Because they performed less total individual limb work during double support, elderly subjects used a greater percent of double support individual limb work for step-to-step transitions [56% (SD 9)] than young subjects [46% (SD 9)] across the range of speeds (P = 0.028). Because of transition work, both young and elderly subjects performed more individual limb work during double support than during single support despite the smaller fluctuations in kinetic energy and gravitational potential energy during double support (Fig. 6C vs. Fig. 4B).

**DISCUSSION**

This study demonstrates that the greater metabolic cost of walking in elderly adults is not due to the amount of mechanical work performed by the limbs on the center of mass. In agreement with many past studies (28, 35, 37, 54), we find that elderly adults consume on average nearly 20% more metabolic energy per kilogram to travel a meter than young adults across a range of speeds. Contrary to our hypothesis, elderly adults perform less individual limb work during double support than during single support despite the smaller fluctuations in kinetic energy and gravitational potential energy during double support (Fig. 6C vs. Fig. 4B).

**Fig. 4.** For the single-support phase, individual limb work (Wlimb,ss; A), magnitude of positive fluctuations in gravitational potential energy (ΔGPEss; B), ratio of individual limb work to the work required to lift and accelerate the center of mass (Wlimb,ss/ΔGPEss + ΔKEss; C), and phase angle between gravitational potential energy maximum and kinetic energy minimum vs. speed (D) in young subjects (●) and elderly subjects (○). Values are means (SD). Lines are least squares regressions. *Significant differences in ΔGPEss between young and elderly subjects at a given speed, (P < 0.05).

**Fig. 5.** Representative data for total energy (Etot), kinetic energy (KE), and gravitational potential energy (GPE) of center of mass vs. time at 1.3 m/s for young (A) and elderly (B) walkers. A single step from heel strike of one foot to heel strike of opposite foot is shown. Energy values are normalized to body mass.
over, while the difference in cost of transport between elderly and young adults increases at faster walking speeds (Fig. 1), individual limb work increases less steeply with speed in elderly adults than in young adults (Fig. 3). These observations suggest that other mechanical factors, such as changes in the metabolic cost of stabilizing the body, the amount of cocontraction, the efficiency of the muscular system, or the metabolic cost of generating force to support body weight, may underlie the greater metabolic cost of walking in elderly adults.

We based our hypothesis, in part, on previous reports that elderly adults tend to spend more time in double support (14, 29, 41, 48) and walk with wider steps (12, 22, 41) because these factors can affect how much step-to-step transition work a walker performs to redirect the center of mass from one inverted pendulum arc to the next (17, 19). However, contrary to those previous studies, we find that elderly adults do not take significantly wider steps and do not spend significantly more time in double support than young adults at the same speed. It is possible that previous observations of differences in step width and double-support time were related to pathologies rather than age itself. By this argument, the reason why we did not observe differences in the present study is that our elderly subjects were healthy and physically active. Moreover, in contrast to our study that compared young and elderly adults walking at the same absolute speeds, most previous studies have compared double-support time in young and elderly adults at their preferred speeds (14, 29, 41). Because double-support time decreases with speed, the difference attributed to age might have been caused by the substantially slower preferred speed of elderly adults. Finally, our step width results may differ from those of prior studies (12, 41) because we used center of pressure data rather than video kinematic data to quantify step width. It is possible that we did not find an age-related difference in step width due to differences in the movement of the center of pressure under the stance foot in elderly adults compared with young adults. We used center of pressure data to calculate step width because it has been previously shown that individual limb work depends on the mediolateral distance between the ground reaction force vectors acting under each foot (17).

Elderly adults perform less individual limb work over a step of walking because they perform less work for forward acceleration during the double-support phase than young adults (Figs. 5 and 6C). Elderly adults slow down and speed up less during double support than young adults. These smaller speed fluctuations and the reduction in double-support individual limb work may result from elderly adults taking shorter steps (7, 38, 39). However, in terms of metabolic cost, the reduction in individual limb work from taking shorter steps is likely partially offset by an increase in internal work performed to swing the limbs at faster step frequencies (7, 38–40). The fluctuations in kinetic energy associated with these speed fluctuations during double support increase with speed less rapidly in elderly adults than young adults (Fig. 6C) and thus help explain why individual limb work increases with speed less rapidly in elderly adults (Fig. 6A).

In contrast to the substantial work performed during the double support, elderly and young adults perform very little individual limb work during single support because they exchange a considerable amount of mechanical energy via the inverted pendulum mechanism. We did not specifically quantify “mechanical energy recovery” for the single-support phase (11) because, contrary to the assumptions underlying the definition of recovery, the total energy of the center of mass is not the same at the start and end of single support (Fig. 5). However, our observation that gravitational potential energy and kinetic energy fluctuate to a similar extent and mostly out of phase during single support suggests that substantial inverted pendulum energy exchange is possible. Indeed, elderly and young adults perform 80% less individual limb work than needed to lift and accelerate the center of mass (ΔGPEws + ΔKEws) during single support, indicating that both groups...
conserve substantial energy by inverted pendulum energy exchange.

Although previous studies have estimated the total mechanical work performed by elderly adults during walking using the traditional “external work” calculation (26, 37, 50), our study is the first to examine individual limb work during walking in elderly adults. Because individual limb work accounts for the opposing simultaneous work performed by the two limbs during double support, it provides a better estimate of the mechanical work performed by the stance limb muscular system on the center of mass (17, 18) and is more closely correlated with the metabolic cost of walking than external work (17, 18). For example, both individual limb work rate and metabolic rate increase with the second power of step width while external work does not change with step width (18). The strong relationship between metabolic cost and individual limb work in walking suggests that other factors more than compensate for the low individual limb work and thereby cause elderly adults to consume more metabolic energy to walk than young adults.

Because some evidence suggests that elderly walkers are less stable than young walkers (22, 32, 55), it makes sense that they may consume more metabolic energy to stabilize themselves during walking and therefore have an elevated metabolic cost of walking. The metabolic cost of lateral stabilization comprises ~6% of the metabolic cost of walking in young adults (18) but has not yet been measured in elderly adults. Because aging typically involves impairment of visual and vestibular function (45, 49, 51), it is likely that elderly adults adopt new, metabolically more expensive, strategies for stabilizing the body during walking (3, 12). However, this idea seems to be contradicted by the observation that stride time variability, assumed to be an indicator of instability, is not correlated with the metabolic cost of walking in elderly adults (33). Nonetheless, some metabolically expensive responses to instability that are not apparent in kinematic analyses, such as increased cocontraction of antagonist muscles (25, 30, 31, 37), may contribute to the greater cost of walking in elderly adults.

It is possible that elderly walkers consume more metabolic energy to perform mechanical work than young walkers because of changes in antagonist muscle coactivation or muscle efficiency. For example, if elderly adults coactivate more opposing muscle pairs during walking than young adults (37), the individual agonist muscles must perform extra work and therefore consume more metabolic energy to overcome the opposing work by their antagonist counterparts. This extra work would not appear as individual limb work because the coactivated antagonist would absorb it. Moreover, cocontraction of some antagonist leg muscles appears to increase with speed more rapidly in elderly adults than young adults (37), and thus it may contribute to the greater difference in metabolic cost of transport between elderly and young adults at faster speeds (Fig. 1). Similarly, a decrease in the efficiency of the muscles themselves with age would require each muscle to consume more metabolic energy to perform a given amount of mechanical work (13, 34, 37). Thus either increased antagonist cocontraction or decreased muscle efficiency would cause elderly adults to consume more metabolic energy for mechanical work during walking than young adults even though they perform less total individual limb work.

Another important role of the muscles during walking is to generate force to support body weight, and it is possible that a greater metabolic cost of force generation contributes to the high cost of walking in elderly adults. In young adults, the metabolic cost of generating muscle force to support body weight accounts for as much as 28% of the net metabolic cost of walking (23). A main determinant of this cost is stance limb geometry. When the stance limb is more flexed, extensor muscles have a lower mechanical advantage and must generate greater joint torques and muscle forces to exert a given force on the ground (4). Although we did not determine joint torques, it is known that the total support torque (i.e., the sum of ankle, knee, and hip torques) is similar for elderly and young adults (16). Thus a change in the overall geometry of the stance limb probably does not contribute to the high metabolic cost of walking in elderly adults. The metabolic cost of supporting body weight may also be affected by the observed shift in the contributions of the individual joints to the total support torque so that elderly adults have higher hip torques and lower ankle torques than young adults (16). Because the hip extensors have longer fibers and shorter tendons than the ankle extensors (47), walkers must activate a greater muscle volume and consume more metabolic energy to generate a given muscle force with the hip extensors than with the ankle extensors (46). Thus the observed redistribution of force generation from the ankle extensors to the hip extensors (16) may increase the metabolic cost of supporting body weight during walking in elderly adults compared with young adults.

In conclusion, changes in individual limb work do not underlie the nearly 20% greater consumption of metabolic energy for walking by elderly adults than young adults. In fact, elderly adults perform ~10% less individual limb work for walking than young adults. Other factors such as a greater metabolic cost of stabilization, greater antagonist muscle cocontraction, reduced muscle efficiency, and/or a greater cost of generating force to support body weight may play key roles in elevating the metabolic cost of walking in elderly adults.

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REFERENCES